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# Moon Plants as Model System for Life Support to Enable Human Exploration

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## Abstract

We propose to develop a plant growth chamber for the Moon. Our goal is to support germination over a 5-day period in a spacecraft on the Moon. The system will validate the ability of plants to provide fundamental life support for future human exploration. The autonomous system provides basic environmental control to grow the plants under harsh lunar conditions characterized by high radiation and partial gravity.

Several innovative technologies are brought together for this lunar plant growth module; solar concentrators that allow light to get to the plants while increasing the power of solar arrays by 2-3 times, wireless communications that allow a sealed environment to communicate with the spacecraft, and a strain of plants tailored to survive lunar night.

This integration of new technology to support plant growth ultimately contributes to human exploration.

**Keywords:** Moon; life support systems; plants; Arabidopsis; Human Exploration

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## 1. Introduction

In this post-shuttle era, the long term vision of NASA is to promote the exploration of the Moon, Mars, and beyond by relying heavily on private for-profit enterprise to develop launch vehicles, passenger carrying capsules, and probes to deep space. In keeping with this vision, we are developing a small, lightweight plant habitat to grow plant seedlings on the Moon. The goal is to demonstrate plant germination on the Moon, using in-situ lunar resources. In addition to being visually fascinating, our growing plants will provide a sound scientific experiment demonstrating fundamental aspects of plant growth at one-sixth gravity in a harsh lunar radiation environment. We will germinate *Arabidopsis* and other seeds in a small self-contained and autonomously operating habitat atop a lander on the Moon's surface. The experiment can be performed within a single lunar day once the mission lands and deploys. Our habitat will fit within the weight, size and power constraints imposed on lunar payloads and will

complement the Google X-Prize mission by generating valuable scientific data that will be useful for the eventual habitation of the Moon by humans.

## 2. Launch configuration of the Habitat

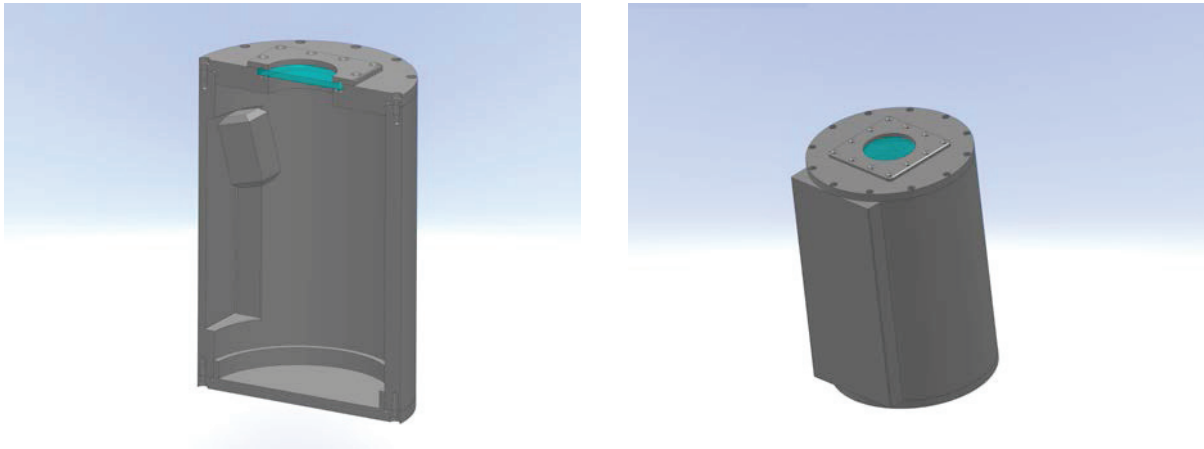


Fig. 1. (a) Internal view of the upper habitat showing camera position on upper left. The light window is at the top. The plants will grow in the footprint at the bottom of the chamber. Total chamber volume is approximately 300 ml. The lower chamber holding the water bladder and electronics is not shown. (b) External view of the habitat. The cylindrical insulated wall is to the right. The flat panel on the left will radiate heat away from the shaded side of the habitat.

Our habitat (see Fig. 1) will consist of a single two-part chamber riding atop a Moon Express lander [1] to be ready for launch to the Moon in mid-late 2014. MoonEx is a leading contender for the Google X-Prize and will ferry multiple payloads to the lunar surface. The habitat will be affixed to the top of the lander where it will operate mostly autonomously. Dry seeds in the habitat will allow us to delay initiation of the experiment until after launch and transit to the Moon. The inactive habitat can endure launch vibrations and transit temperature fluctuations without need for power or communications. MoonEx will provide all landing operations, lander orientation, and Moon-Earth communications downlink after arrival on the lunar surface.

## 3. The Payload and Lunar Operations

After landing on the Moon, an internal timer will trigger the micro-fluidics system to release water into the seed module contained within the upper sealed portion the habitat. The temperature-regulated upper chamber will provide nominal earth atmosphere. Once hydrated, the seeds will germinate and grow towards lunar sunlight provided by a window and solar collector at the top of the habitat. Solar concentrators and visor-like coatings will filter the wavelengths needed by the seedlings, using the remainder to power the habitat. A camera will snap time-lapse photos of the seedlings and send them to Moon Express's downlink via a wireless communications system. As proof that the habitat is actually on the Moon, Moon Express may point one of their cameras at our habitat as a secondary image capture.

Daily photos will show the first life to put down roots on the Moon. Approximately 100 seeds will germinate in a habitat near the size of a normal Coke<sup>®</sup> can. Image return will be accompanied by sensor-based housekeeping data including temperature, atmosphere integrity, and relative humidity. At the end of the lunar day (equivalent to fourteen earth-days of continuous daylight), the habitat will succumb to lunar darkness and terminate the experiment. Our data, consisting of only images and environmental information, will be sufficient for determination of plant growth rates and patterns, thus providing an extension of knowledge of how plants cope with novel lunar environmental conditions. Our one-sixth g studies will complement ongoing International Space Station (ISS) microgravity experiments and 1 g earth-based data.

## 4. Main Technical Challenges

Though scientific aspects of the experiment may seem straightforward, technological elements needed for mission success are challenging, especially considering that the operations are occurring on the harsh lunar surface. Uplink commanding will not be available for the complex operations of the habitat. Furthermore, the sun will track across the lunar sky, thus demanding autonomous adaptive control of several parameters crucial to maintaining life support conditions. Very restricted upmass coupled with extraordinarily high launch costs limit options for controlling environmental conditions and even basic habitat functions. Complex adaptive systems must be self regulating and sufficiently robust to meet the continuous needs of the growing seedlings throughout the constantly changing lunar day. The main technical challenges addressed by the flight unit, and their solutions, are:

### 4.1. Regulate the growth chamber temperature to between 22°C and 27°C.

Because there is essentially no atmosphere on the Moon, ambient lunar temperatures can vary widely depending on incident sun exposure. Surfaces facing sunlight can exceed 107°C while surfaces facing away from the sun can dip to -153°C. Cold internal temperatures will prevent or slow seed germination and growth, thus impacting data collection. Freezing while on the lunar surface may kill the seedlings or damage the growth module. Excessive temperature within the habitat will injure or kill the seedlings. Excessive hot or cold temperatures may also damage system electronics. The outer wall of the thin-walled metallic cylinder will be covered with multiple layers of insulation, except for a single band of surface that will be pointed away from incident sunlight. Most of the infrared heat striking the sides of the habitat will be reflected, although a small amount of heat will be conducted to the habitat interior. Thermal modeling based on habitat dimensions and insulative material combined with irradiation details gleaned from old Apollo records [2] has resulted in the design shown in Fig.1. The narrow band pointing away from incident light will transmit heat away from the habitat interior. Calculations indicate that the uncontrolled habitat would run approximately 2-4°C colder than the target temperature of 22°C. Small heater loops within the habitat that are powered by external photovoltaics and controlled by sensor feedback, will provide makeup heat to maintain the desired temperature range. The seedlings, themselves, are sufficiently dynamic to accommodate temperatures in the specified range. Thermal regulation may well be the most challenging aspect of environmental control. Careful modeling coupled with extensive earth testing will lead to a robust lightweight adaptive system.

### 4.2. Lighting level available to the seedlings (100-400 $\mu\text{E m}^{-2} \text{s}^{-1}$ about 1/10 of full earth sunlight).

Since there is no atmosphere, lunar light intensity is very high; Apollo astronauts used visors that transmitted only 8.5% of incident light. Seedlings within the habitat will see varying intensity as the sun tracks through the lunar day. The limited size of the window and solar collector at the top of the habitat will allow for *in-situ* light utilization (a basic tenet for future lunar greenhouses) as well as illumination for pictures. The same type of visor coatings currently used on ISS spacesuits will be used to prevent excessive light and resultant photobleaching of the seedlings. Variance in light intensity through the lunar day will have only a slight impact on photosynthetic surface area of the seedlings.

### 4.3. Camera system (0.1 mm resolution on the plants).

Because there will be no uplink commanding, the system will need to be autonomous and adaptive to changing light conditions. Small lightweight cameras are available with auto-exposure features. We will use a pre-focused (see below) camera with sufficient depth of field to visualize seedling detail. Computer control will snap images every 12 hours starting from 96 hours to 144 hours (4-6 earth days) after initial hydration. More images will likely be acquired beyond 144 hours, depending on bandwidth availability from the lander. Camera zoom features will not be necessary with sufficient camera resolution. The camera image will cover the entire internal floor of the habitat. Using wireless communications, images will be sent from the habitat to the lander communications system for transfer to the earth.

#### *4.4. Current to a heating coil to avoid condensation for imaging.*

The Camera will be positioned inside a chamber with near-saturated relative humidity. To prevent condensation droplets from forming on the camera lens, and thus interfering with imaging, a heated window will be necessary. Evaporation of condensation droplets from imaging windows is routinely used in ISS plant habitats. The heated window only needs to be about 1°C above ambient to prevent condensation. Control of heater operation can be timed with the imaging sequence described above. Self-focusing cameras prefer to focus on sharp condensation droplets. For this reason, we will utilize a camera pre-focused on the level of the seedlings.

#### *4.5. Air-tight seal holding sea level pressure against space vacuum.*

The habitat internal volume will be held at earth ambient 1 atmosphere. Mated surfaces will be necessary in order to assemble the habitat and insert seeds prior to launch. Plant seedlings can easily tolerate slight changes in barometric pressure [3] caused by temperature fluctuations. Though sealing mated surfaces may be relatively straightforward, loss of atmospheric pressure would be catastrophic to the experiment. Any sealing agents (high vacuum grease, or silicones) will need thorough biocompatibility testing prior to use (see below). Prototypes and even the final assembled flight unit will need to undergo shock and vibration testing to demonstrate mechanical strength needed to survive launch and lunar landing.

#### *4.6. Reliable injection of water (5-10 ml) on command.*

Water will be loaded into a flexible storage bladder that will be contained in the lower habitat section. A small lightweight fluidics pump will, on command, move water from the bladder to the seedling growth module in the upper chamber. Commanding of the pump may come from the MoonEx bus as a single one-time pulse following landing on the Moon. Alternatively, pumping may be self-initiated following detection of 1/6 gravity for a prescribed duration. Ames Research Center has extensive experience in design and dynamic operation of micro-fluidics systems in space [4].

#### *4.7. Sterile habitat interior and surface-sterilized seeds.*

Prior to launch, all habitat components that may come in contact with the seedlings will need to undergo sterilization treatment to insure that competing organisms (bacteria, fungi) are not present. Where permissible, components will be autoclaved. Parts that cannot be autoclaved, such as plastics, will be sterilized with ethanol. Seeds can be surface-sterilized with Chlorox<sup>®</sup>. Sterilization of plant habitats is routine and critical to mission success [5].

#### *4.8. Radiation hardened mechanical and electrical components.*

The highly complex radiation environment in space beyond near-earth orbit is comprised of electromagnetic radiation and charged particles from the sun and galactic origin. These particles can wreak havoc on deep space payloads, including lunar missions, beyond shielding by Earth's magnetic fields. Extensive radiation shielding of the habitat is not possible due to the added upmass and cost. Use of commercial radiation-hardened materials, where practical and cost effective, is one way to reduce risk from radiation damage to system electronics.

#### *4.9. Overall biocompatibility of system components with seeds and seedlings.*

Plants and all biological systems are highly susceptible to interference from environmental contaminants. In high concentrations, even relatively benign materials (salts, for example) can adversely affect growth. Plants are especially sensitive to ethylene gas (C<sub>2</sub>H<sub>4</sub>), a naturally occurring plant hormone active at low parts per billion concentrations. Additionally, other uncharacterized materials offgassing from adhesives, plastics, conformal coatings and other sources can severely affect seeds and seedlings. Extensive experience in building plant habitats has shown little predictability in identifying which materials are detrimental. A critical element of this lunar habitat will be thorough biocompatibility testing to ascertain that all habitat components are compatible with *Arabidopsis*

and other seeds and seedlings.

## 5. Innovative technology incorporated into the habitat

Four new technologies will be included in the habitat design.

### 5.1. *Novel Space Biology.*

The *Arabidopsis* strain used in the habitat is the culmination of approximately 10 years of plant breeding effort, resulting in a plant line characterized by extremely high and reliable percent germination, vigorous plant growth and high fertility. The strain is genetically dwarf enabling seedlings and even mature plants to grow in very confined space typical of small sized habitats. While only seedlings will be generated in this initial attempt to grow plants on the Moon, the *Arabidopsis* germplasm has already been biologically engineered, via conventional plant breeding, to survive lunar night [6] and generate seeds [seed-to-seed survival] in only 3 lunar days. Anticipated future deep space experiments will make use of the engineered plant's full potential. In essence, the preferred model organism of plant biologists (*Arabidopsis*) has already been bioengineered to specifically perform in space experiments. Plants eventually grown in deep space for future human food and gas recycling will need to possess many of these same characteristics.

### 5.2. *Sustainable Power.*

Solar arrays attached at the base of the habitat will provide power for hydration, camera operations and data transmission. Development of a solar concentrator [7] associated with the upper window will allow for reduction of harmful wavelengths and their subsequent conversion to light used by plants. This new technology could provide augmented power contributing to future robotic or crewed missions. The power demands of the habitat are comparatively low. We do intend to include a backup battery (isolated in the lower chamber to avoid offgassing issues) which may assist early power needs of hydration pumping. Overall, we expect the habitat to be power-neutral and independent of energy potentially supplied from the lander.

### 5.3. *Wireless communications.*

Data transmission between the habitat and lander will be via wireless Bluetooth or Zigbee connection. Absence of cabling will result in significant weight saving, reduced volume, through connections, and possibility for radiation damage. Demonstrated use of a Zigbee or other wireless network will be significant for development of future deep space missions.

### 5.4. *Environmental control.*

Already discussed aspects of environmental control, including extreme weight reduction, are derived from a heritage of successful ISS, BION and small satellite missions [4, 5, 8]. Application of these existing technologies to partial gravity environments (Moon, later, Mars) will demonstrate life support for future human exploration of space. Success of our plant habitat will involve integration of multiple existing and new technologies, all contributing to eventual human exploration of space.

## 6. Risk Management

Unlike previous NASA-supported missions to the Moon, the MoonEx venture is designed and operated by private enterprise; indeed, this is the new vision for United States deep space exploration. This paradigm shift directly impacts how risk to mission success is viewed and handled. MoonEx and other potential Google X-Prize contenders are drawing on LCROSS and LADEE heritage as well as depth from other NASA lunar and space ventures. This will help reduce spacecraft landing and sun orientation risk. Recent launches of SpaceX to the ISS, and return, demonstrate that the private model for risk mitigation can work.

Aspects that reduce risk to the habitat and have been incorporated into our design are:

- Independence from lander, except for data downlink to earth. We do not rely on externally supplied power.
- Small footprint, reduced weight. We can fit on multiple locations. Because we fit anywhere and have few lander demands beyond wireless communications, we could easily move to another Google X-Prize contender, should one become available. We will pay for our ride to the Moon, whoever takes us there.
- Robust thermal regulation. The cooling side of the habitat wall occupies only a small part of the external surface. The larger cylindrical wall can accommodate minor orientation errors when landing on the lunar surface. Our interior will intentionally run cool with makeup heat regulated by feedback sensors.
- Tiered data return. Our goal, to show that plants can germinate, grow, and thrive on the lunar surface, can be accomplished with a single returned image. We anticipate a time-lapse sequence of images spanning 144 hours (hopefully more) that will allow us to show growth rates on the Moon. Finally, time lapse images will show plant responses (tropisms, circumnutations) to the changing lunar environment which we can use to compare with growth here on earth.
- Multiple plant species. In addition to *Arabidopsis*, the preferred model organism for many plant experiments, our habitat will contain *Ocimum basilicum* (basil) seedlings. Basil germinates extremely quickly and can tolerate temperatures above 27°C. Basil also has a heritage [ 9] in other NASA spaceflight experiments.
- Biologically engineered organism. Like the structural aspects of the habitat, *Arabidopsis* has been genetically tailored to grow well in space.

## 7. Significance and future Research Perspectives

NASA intends to promote future human exploration of space. Why plants, then, and why on the Moon? This will be the first attempt to export earthly life to a planetary body beyond near-earth orbit, where it will grow and thrive. Plants are multicellular organisms as are humans, and their germination and gene expression is relevant to understanding the development of multicellular life on other worlds. As well, their survival is relevant to all organisms, and will provide food and resource recycling that will enable future human exploration of space. Because of their dormant seed phase, rapid growth, and ability to tolerate environmental extremes, they are the preferred first organism to export to deep space. Sustained plant life on the Moon ultimately enables human space exploration.

Ancillary to the science return, NASA will promote a parallel education outreach effort that will run in real-time with the Moon experiment. We anticipate STEM participation as students, scientists, and politicians will be inspired by seeing plants living on the Moon. Impact can be measured by the amount of involvement of K-12 education in real-time observations of plant growth. Previous NASA ISS outreach plant programs have been immensely successful [9, 10]. People, including astronauts, like to watch plants grow. Just ask any home gardener. Plants, as living companions to space travellers, have been repeatedly cited [11] as significant to future successful space missions.

This short-term plant experiment is keyed to an initial Moon lander platform not expected to survive lunar night. Future missions will achieve longer duration, ultimately surviving repetitive lunar day-night cycles. The enabling technology of this first attempt will ultimately drive seed-to-seed plant survival on the Moon, which in turn, will enable very long term human exploration beyond our earthly world.

Development of extremely small, self-powered, cheap plant habitats may also be useful for study of extreme environments here on earth. Habitats could be deployed in remote locations such as Antarctica to study high-latitude Coriolis effects on plant growth. Students around the world could use these habitats to gain hands-on experience working with real living organisms.

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## References

1. Moon Express, Moon's First Enterprise. <http://moon.express.com> [last visited 7/25/2012].
2. Lunar Sourcebook: A User's Guide to the Moon. Cambridge: University of Cambridge Press, 1991.
3. R. Ferl, A. Schuerger, A. Paul, W. Gurley, K. Corey, R. Bucklin, Life Support Biosph. Sci. 8 (2002) 93-101.
4. K. Millar, P. Kumar, M. Correll, J. Mullen, R. Hangarter, R. Edelman, et.al, New Phytologist 186 (2010) 648-656.
5. J. Kiss, p. Kumar, K. Millar, R. Edelman, Adv. Space Res. 44 (2009) 879-86.
6. R. Bowman, G. Sun, Gravitational and Space Biol. 21 (2007) 32 (abst).
7. V. Sholin, J. Olson, S. Carter, J. Applied Physics, 101 (2007) 123114.
8. PharmaSat. [http://www.nasa.gov/mission\\_pages/smallsats/pharmasat/main/index.html](http://www.nasa.gov/mission_pages/smallsats/pharmasat/main/index.html) [last visited 7/25/2012].
9. NASA Engineering Design Challenge. <http://www.nasa.gov/audience/foreducators/plantgrowth/home/index.html> [last visited 7/25/2012].
10. NASA basil seeds on the move.  
[http://www.nasa.gov/audience/foreducators/plantgrowth/home/M\\_STS118\\_Basil\\_Seeds\\_on\\_the\\_Move.html](http://www.nasa.gov/audience/foreducators/plantgrowth/home/M_STS118_Basil_Seeds_on_the_Move.html) [last visited 7/25/2012].
11. S. Bates, J. Marquit. The benefits of plants: A review of the literature and application to habitation systems for humans living in isolated or extreme environments.  
<http://www.sdl.usu.edu/downloads/posters/vpu-plant-benefits.pdf> [last visited 7/25/2012].